

The contribution of the hadronic component of the photon into the D^* -meson photoproduction at HERA.

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In the framework of the vector dominance model (VDM) new contribution into the cross-section of D^* -meson photoproduction at HERA has been estimated. This contribution is due to the interaction of the virtual vector $c\bar{c}$ -mesons from photon with the proton. It has been shown that the mechanism under discussion plays the essential role for all values of transverse momentum of D^* -mesons at HERA. Taking into account for the contribution of this mechanism improves the description of the experimental cross section distribution.

1 Introduction

One of the most interesting features of the charm photoproduction at HERA, which had been discovered by ZEUS Collaboration, is the correlation between jet energies in the events with the D^* -meson [1].

It was shown experimentally that in the kinematical region $130 < W < 280$ GeV, $Q^2 < 1$ GeV 2 (where W is the energy of the γp -interaction, and Q^2 is the photon virtuality) in $\sim 30\%$ of all events with D^* -mesons two jets with the highest transverse energy take away only a half of the photon energy. The distribution over x_γ^{OBS} has been used for the quantitative analysis of this phenomenon. The value of x_γ^{OBS} means the part of the photon energy which is taken away by two jets with the highest transverse energy. It is defined as below:

$$x_\gamma^{\text{OBS}} = \frac{\sum_{\text{jet}=1,2} E_T^{\text{jet}} e^{-\eta_{\text{jet}}}}{2E_e y}, \quad (1)$$

where the η^{jet} – pseudorapidity of the jet, E_T^{jet} – transverse energy of the jet. One takes the sum over two jets with the highest E_T^{jet} .

The following equation allows to clarify the physical meaning of x_γ^{OBS} :

$$2E_e y = \sum_{\text{jet}}^{\text{all}} (E_T^{\text{jet}} - p_z^{\text{jet}}) = \sum_{\text{jet}}^{\text{all}} E_T^{\text{jet}} \cdot e^{-\eta_{\text{jet}}}. \quad (2)$$

One can see that for events with two jets $x_\gamma^{\text{OBS}} \equiv 1$. For events with many jets always $x_\gamma^{\text{OBS}} < 1$.

In the framework of the pQCD there are two types of contribution into charm photoproduction:

- 1) contribution from the scattering of the parton from the hadron on the photon ("direct photon");
- 2) contribution from the scattering of the parton from hadron on the parton from photon ("resolved photon").

For the "direct photon" events $x_\gamma^{\text{OBS}} \sim 1$. This effect can be easily understood if one keeps in mind that in the LO such events have only two jets.

In the "resolved photon" events or, by other words in the interaction of the hadronic parton with the charm quark from photon, the charm quark carries only a part of the photon energy, and that is why x_γ^{OBS} can be essentially less than 1.

In the NLO approach one can not distinguish between the contributions from "direct photon" and "resolved photon" on the level of the cross-sections, and NLO matrix element includes both of these contributions [2, 3].

Nevertheless, these contributions have a different kinematical behavior and can be distinguished one from another by using the distribution over x_γ^{OBS} . So, ZEUS collaboration divides the x_γ^{OBS} range into two parts:

- 1) $0 < x_\gamma^{\text{OBS}} < 0.75$ ("small" x_γ^{OBS}) which corresponds to the "resolved photon" events;
- 2) $0.75 < x_\gamma^{\text{OBS}} < 1$ ("large" x_γ^{OBS}) which corresponds to the "direct photon" events.

As it follows from the ZEUS data, for the kinematical region $p_T^{D^*} > 3$ GeV, $|\eta^{D^*}| < 1.5$, $130 < W < 280$ GeV, $Q^2 < 1$ GeV 2 , $|\eta^{\text{jet}}| < 2.4$, $E_T^{\text{jet}1} > 7$ GeV, $E_T^{\text{jet}2} > 6$ GeV a

noticeable discrepancy between the NLO predictions for the distribution over x_γ^{OBS} and the experimental one exists [2, 4]. The experimental value of the cross-section in the region $0 < x_\gamma^{\text{OBS}} < 1$ (region of "resolved photon") is larger than that predicted by the NLO approach.

In this paper we will try to describe the distribution over x_γ^{OBS} by taking into account the hadronic component of the photon in the framework of the Vector Dominance Model (VDM) [5, 6].

2 Description of the model and results

First of all, it is worth to mention that we have to take into account only photon charm quark fluctuation, because we are interested in the events with the charm jets only. In our calculation we suggest that the main contribution into the D^* -meson photoproduction at HERA in the region of "small" x_γ^{OBS} is due to the scattering of gluon on the c -quark from the J/ψ , ψ' and other vector $c\bar{c}$ -mesons from photon in the wavefunction of the initial photon.

In the case under consideration the photon wave function can be approximated by a sum of the wave functions of the vector mesons as bellow [5, 6]:

$$|\gamma\rangle = \sum_{V=\psi, \psi', \psi(3770)\dots} \frac{4\pi\alpha}{\gamma_V^2} |V\rangle, \quad (3)$$

where a γ_V constant is determined by the vector meson width of decay into the e^+e^- -pair:

$$\Gamma(V \rightarrow e^+e^-) = \frac{\alpha^2}{3} \frac{4\pi}{\gamma_V^2} M_V \quad (4)$$

From the equations above the charm photoproduction cross section can be expressed through cross-sections of the vector meson interaction with hadron:

$$\sigma(\gamma N \rightarrow c\bar{c}) = \sum_{V=\psi, \psi', \psi(3770)\dots} \frac{4\pi\alpha}{\gamma_V^2} \sigma_{\text{inel.}}(VN) \quad (5)$$

As it was mentioned above, one should take into account only the $c\bar{c}$ -mesons contribution, as the contribution from other vector mesons is small [6].

So, in the framework of VDM, the following equation can be written for the charm photoproduction with two large transverse energy jets:

$$\sigma(\gamma p) = \sum_{V=\psi, \psi', \psi(3770)\dots} \frac{4\pi\alpha}{\gamma_V^2} K(E_\gamma, m_V, m_p) \cdot \sigma(Vp), \quad (6)$$

where

$$\sigma(Vp) = \int \int f_c^V(x_\gamma^{\text{OBS}}) f_g^N(x_g) \sigma(cg \rightarrow 2 \text{ jet}_{\text{higt E}_T}) dx_\gamma^{\text{OBS}} dx_g, \quad (7)$$

and

$$K(E_\gamma, m_V, m_p) = \sqrt{\frac{E_V^2 - m_p^2}{E_\gamma^2}}. \quad (8)$$

To evaluate the $\sigma(cg \rightarrow 2 \text{ jet}_{\text{higt } E_T})$ we use the Born approximation for the $cg \rightarrow cg$ elastic scattering. So, the cross-section for the events with two high E_T jets is determined by the hard scattering of the gluon on the c -quark from vector meson, as it has been shown in Fig. 1.

For the p_T -distribution of D^* we convolute this cross section with the fragmentation function of c -quark into D^* -meson from [4].

For the c -quark distribution in J/ψ and any other vector $c\bar{c}$ -meson we use the Regge parametrization [7]:

$$f_c^\Psi(x) = Nx^{-\alpha_\Psi}(1-x)^{\gamma-\alpha_\Psi}, \quad (9)$$

where x is the J/Ψ momentum fraction of c -quark, α_ψ is the intercept of J/ψ , N is the normalization coefficient and $\gamma = 1/4$.

The best description of the charm production at small p_T can be achieved for $\alpha_\psi = -2.2$ [8]. With this value of α_ψ the parametrization has the following form

$$f_c^\Psi(x) = 49.8x^{2.2}(1-x)^{2.45}. \quad (10)$$

It is worth to mention that this quark distribution is a complete analog of the valence quark distribution in ρ -meson:

$$f_q^\rho(x) = Nx^{-\alpha_\rho}(1-x)^{\gamma-\alpha_\rho}. \quad (11)$$

The only difference is the different values for Regge intercept and parameter γ .

Average fraction of the total momentum carried by c -quarks is close to 1:

$$\langle x_c \rangle + \langle x_{\bar{c}} \rangle \approx 0.96, \quad (12)$$

and each quark get approximately a half of the photon momentum.

So, we get the result we needed: in average, only a half of the photon momentum participates in the hard cg -interaction followed by the production of two jets with large transverse energies. Namely such events give the contribution into region of "small" x_γ^{OBS} .

The characteristic time of the $c\bar{c}$ -fluctuation is about $\sim 1/m_\psi$ in the rest frame of fluctuation. This value multiplied by the Lorence factor E_γ/m_ψ is essentially larger than the characteristic time of the hard jet production:

$$\frac{E_\gamma}{m_\psi^2} \gg \frac{1}{E_T^{\text{jet}}}. \quad (13)$$

This circumstance allows us to calculate the charm production cross-section incoherently, summarizing the contributions from hard scattering on each c -quark. It is clear that for small E_T such approach is not valid and it is worth to consider the $c\bar{c}$ -meson as a color dipole and take into account transverse quark motion and interference between different contributions. In this kinematical region the dipole model [9] gives a good description of the data.

In this paper we limited ourselves to the consideration of the incoherent contribution and describe the distributions in p_T and η for $p_T > 4$ GeV.

The cuts on the jets transverse energy for the distribution in x_γ^{OBS} ($E_T^{\text{jet}1} > 7$ GeV and $E_T^{\text{jet}2} > 6$ GeV) ensure large transverse momentum of c -quark before its fragmentation into D^* -meson (or in other words after hard scattering $cg \rightarrow cg$). That is why we use our model for all investigated values of p_T to predict the x_γ^{OBS} distribution.

Our model does not contain any new parameters. Indeed:

1) the photon coupling constants with J/ψ and other vector $c\bar{c}$ -mesons are known from the width of meson decay into e^+e^- ;

2) the c -quark distribution in the vector $c\bar{c}$ -meson (9) contains the Regge intercept $\alpha_\psi(0)$ which determines fragmentation function of c -quark into D^* , and value of $\alpha_\psi(0) = -2.2$ allows to describe the experimental data on c -quark fragmentation into D^* -meson and charm photoproduction at low energies [7];

3) the scale μ_R in the determination of the strong coupling constant $\alpha_s(\mu_R)$ in the hard scattering matrix element for the process $cg \rightarrow cg$ and the scale μ_F for the gluonic structure function are common parameters for such calculations. We use the following values for the scales: $\mu_R = \mu_F = 2m_{D^*}$.

It is worth to mention that the main contribution into the charm photoproduction calculated in the framework of VDM is due to J/ψ (about 60%). Other vector $c\bar{c}$ -mesons give 40% of the total cross-section.

In the frame of the model under consideration the ZEUS experimental cuts $E_T^{\text{jet}1} > 6$ GeV, $E_T^{\text{jet}2} > 7$ GeV are equivalent to the following ones: $E_T^{\text{jet}1}, E_T^{\text{jet}2} > 7$ GeV. The model does not account for the initial transverse momentum of the c -quark into the $c\bar{c}$ -fluctuation, which is about ~ 1 GeV. That is why the both high energy jets have the same transverse energy.

To evaluate the cross-section uncertainty which is due to the transverse momentum of the initial c -quark we have calculated the distribution in x_γ^{OBS} for $E_T^{\text{jet}1}, E_T^{\text{jet}2} > 7$ GeV and for $E_T^{\text{jet}1}, E_T^{\text{jet}2} > 6$ GeV. The difference between two this calculations estimates the theory uncertainty.

One can see from Fig. 2a,b that this uncertainty is rather large.

As one can see from Fig. 2a the description of the experimental data on x_γ^{OBS} -distribution in the region of the "resolved photon" has been essentially improved by adding the VDM predictions with the BKL ones [4].

The slightly better description of the data can be achieved by adding the VDM predictions to NLO ones from [2] (see Fig. 2b). However, one must keep in mind that the adding of the VDM contribution can dramatically enlarge the normalization of the distribution in transverse momentum of the D^* -meson for the model [2].

It is important to mention that hard interaction with the hadronic component of the photon (J/ψ , ψ' and so on) gives the noticeable contribution into the region of large p_T (see Fig. 3). In other words, the attempt to describe x_γ^{OBS} distribution in the framework of VDM leads to additional contribution in the region of large p_T .

So, the following conclusion can be drawn: the nonperturbative $c\bar{c}$ -fluctuations of photon are important for the charm photoproduction. Such fluctuations are described in the framework of VDM and can not be described by simple formula of the pQCD

$$f_c(x) \sim (x^2 + (1-x)^2) \quad (14)$$

or improved formula [10]:

$$f_c(x) \sim \left(x^2 + (1-x)^2 + \frac{2m_c^2}{E_T^2} x(1-x) \right) \quad (15)$$

or Bethe-Heitler formula [11]:

$$\begin{aligned} f_c(x) = & \frac{4\alpha}{3\pi} \left[\beta \left(8x(1-x) - 1 - \frac{4m_c^2}{Q^2} x(1-x) \right) \right. \\ & \left. + \left(x^2 + (1-x)^2 + \frac{4m_c^2}{Q^2} x(1-3x) - \frac{8m_c^4}{Q^4} x^2 \right) \ln \left(\frac{1+\beta}{1-\beta} \right) \right], \end{aligned} \quad (16)$$

if $\beta^2 = 1 - \frac{4m_c^2 x}{(1-x)Q^2} > 0$ and $f_c(x) = 0$ if $\beta^2 < 0$.

This part of the fluctuations has a typical hadronic structure (9) and such fluctuations provide about 30% in the cross-section distribution in x_γ^{OBS} for the D^* -meson photoproduction.

The topology of the events in the region of the "small" x_γ^{OBS} essentially differs from one of the events in the region of the "large" x_γ^{OBS} . In the latter case both jets carry a charm quark, in contradiction with the former case, where only one jet has charm quark. This circumstance leads to the large azimuthal correlation between charmed particles for the "direct photon" and to negligible one for "resolved photon" (see Fig. 4).

3 Conclusion

It has been shown that scattering of virtual vector $c\bar{c}$ -mesons from photon on the proton gives noticeable contribution into the D^* -meson photoproduction for all values of the transverse momentum investigated at HERA. Furthermore this contribution allows essentially improve the description of the experimental distribution in x_γ^{OBS} in the region of the "resolved photon" ($0 < x_\gamma^{\text{OBS}} < 0.75$).

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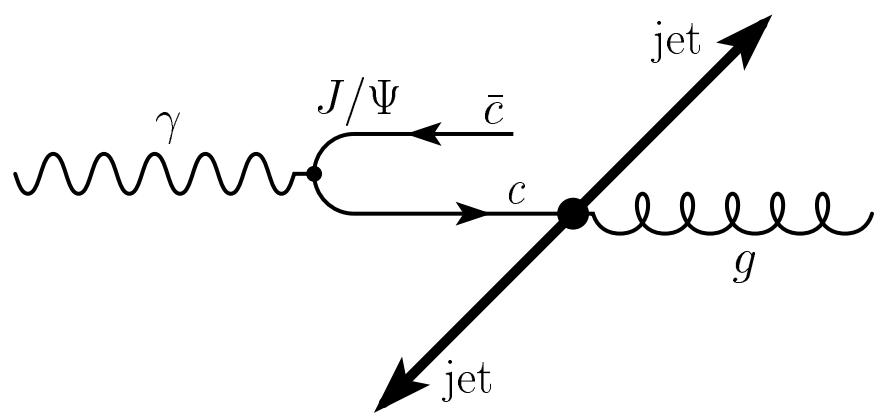


Fig. 1. Charm production scheme in the Vector Dominance Model.

$d\sigma_{\gamma p}/dx_{\gamma}^{\text{OBS}}$, nb

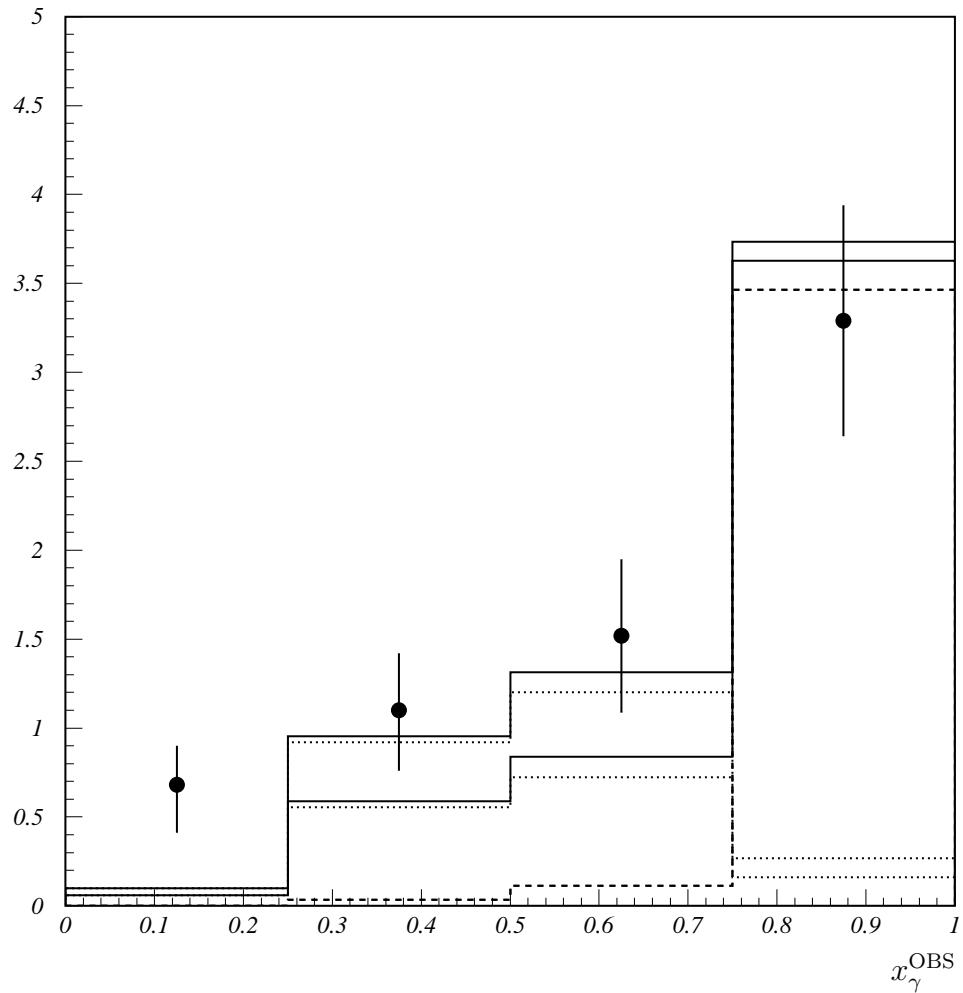


Fig. 2a. The experimental distribution in x_{γ}^{OBS} of the D^* -meson production cross section (ZEUS) in comparison with the BKL predictions [4] (dashed histograms), with VDM predictions (the region between the dotted histograms) and with the sum of BKL and VDM predictions (the region between the solid histograms).

$d\sigma_{\gamma p}/dx_{\gamma}^{\text{OBS}}$, nb

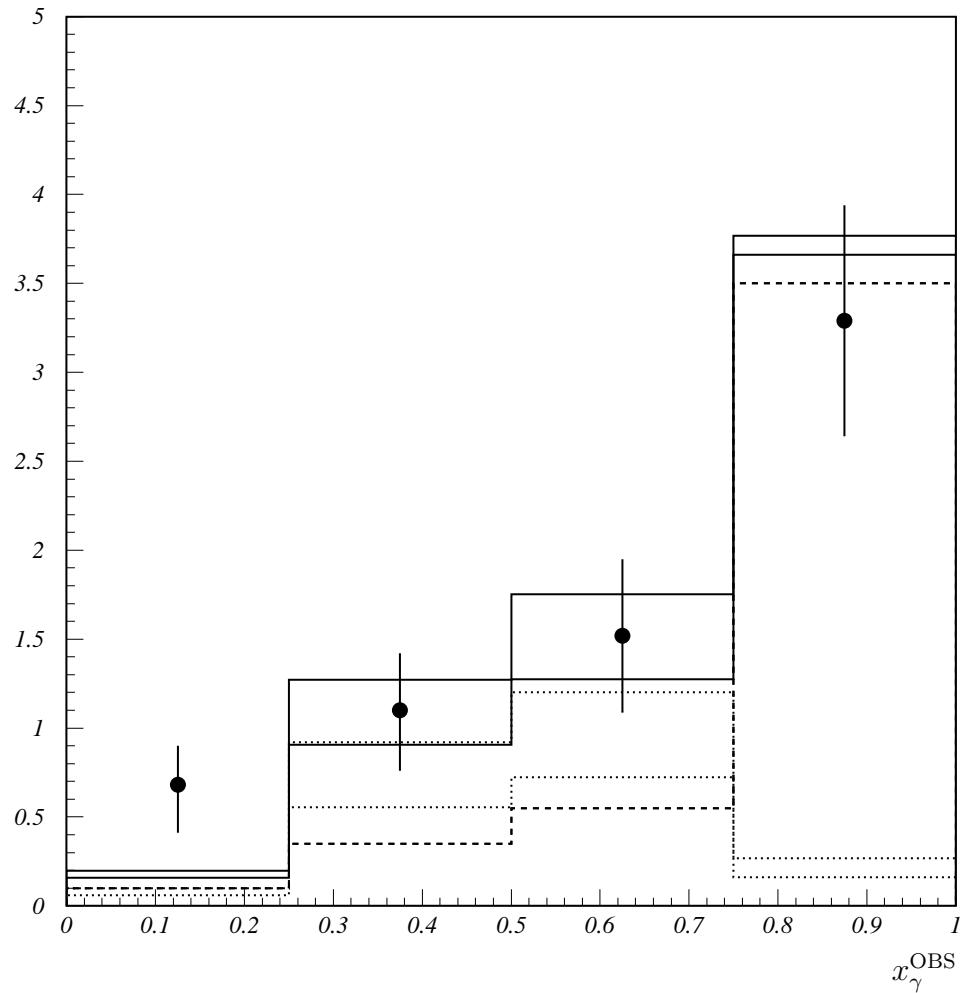


Fig. 2b. The experimental distribution in x_{γ}^{OBS} of the D^* -meson production cross section (ZEUS) in comparison with the Frixione et al. predictions [2] (dashed histogram), with VDM predictions (the region between the dotted histograms) and with the sum of Frixione et al. and VDM predictions (the region between the solid histograms).

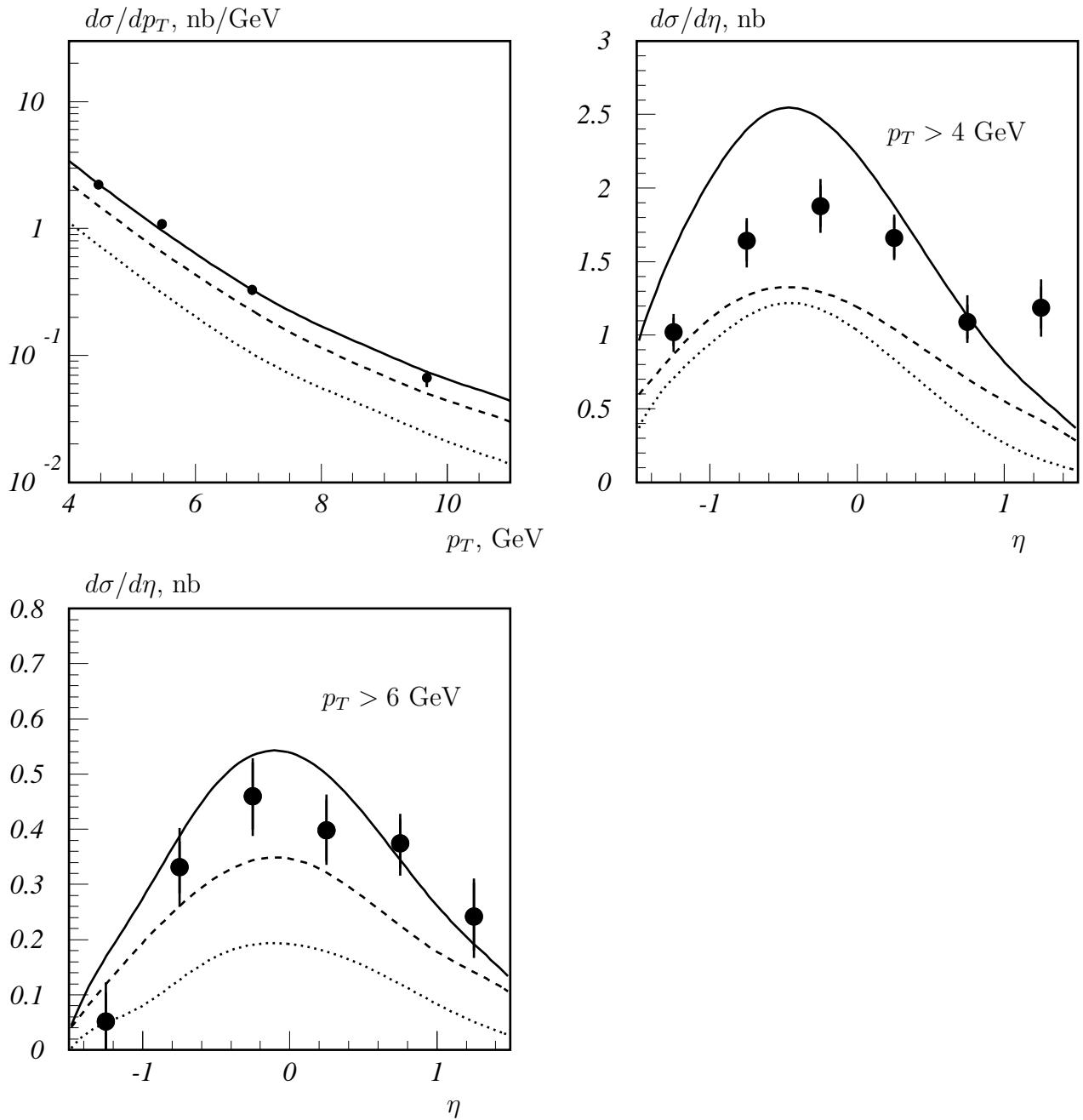


Fig. 3. The experimental distributions of the D^* -mesons photoproduction in transverse momentum (p_T) and pseudorapidity (η) for $130 < W < 280$ GeV and $Q^2 < 1$ GeV 2 in comparison with the BKL predictions [4] (dashed curve), with the VDM prediction (dotted curve) and with the sum of BKL and VDM predictions (solid curve).

$d\sigma_{\gamma p}/d\Theta$, nb

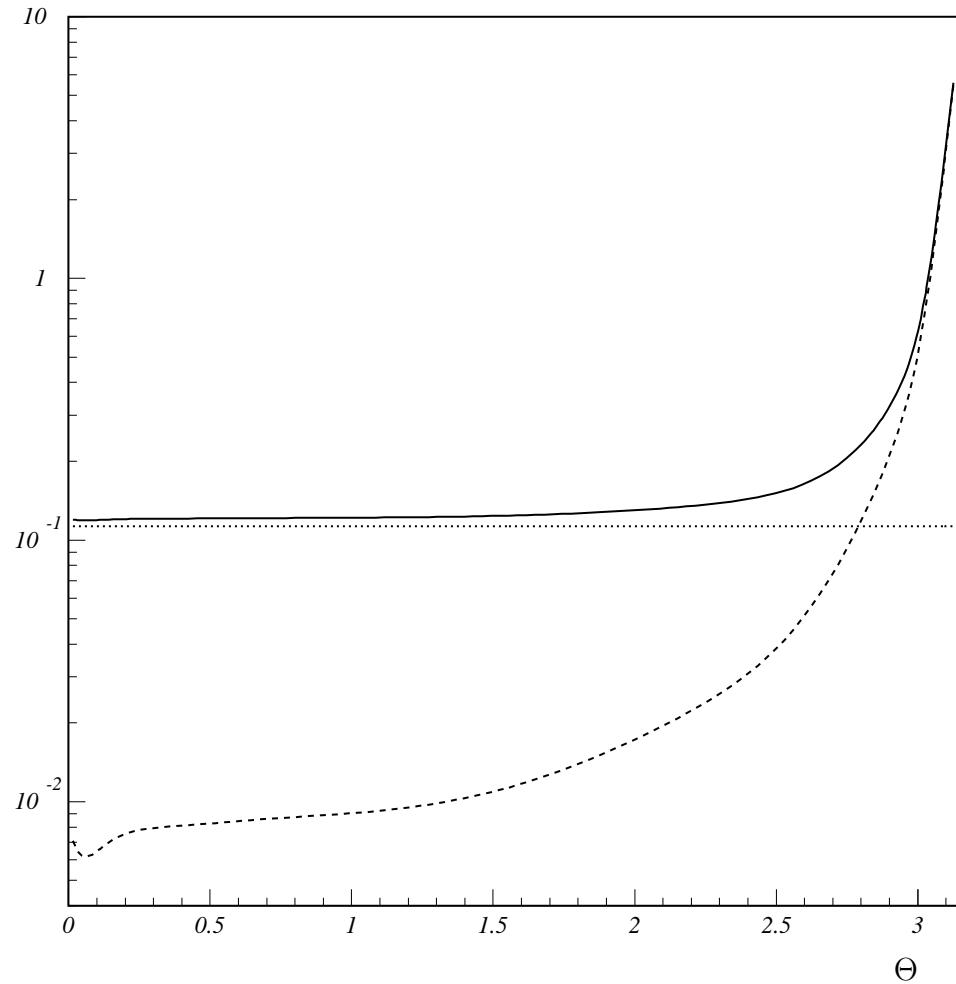


Fig. 4. The azimuthal correlation between two charmed particles for the D^* -meson photoproduction in the kinematical region of $p_T > 6$ GeV (dashed curve is the BKL contribution [4], dotted curve is the VDM contribution, solid curve is the sum of BKL and VDM prediction). Θ is the angle between the transverse momenta of the charmed particles.